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FOR

MODEL-BASED FAULT DETECTION AND ISOLATION SYSTEM AND METHOD

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This application claims the benefit of U.S. Provisional Patent Application No. 60/247,289 entitled FAULT DETECTION AND ISOLATION SYSTEM AND METHOD and filed Nov. 9, 2000.

Technical Field

The present invention is in the field of control system design. More particularly, the present invention is a model-based fault detection and isolation system and method for monitoring overall system performance and diagnosing faults. The system and method of the present invention may be applied to vehicle control systems.

Background and Summary of the Invention

In recent years, increasing interest and requirement for improved vehicle performance, reliability, and safety has focused attention on the use of Fault Detection & Isolation (FDI) when designing vehicle control systems. Fault detection and isolation is becoming one of the most important aspects in vehicle system control design. In order to meet the increasing demand for better performance and reliability, model-based FDI schemes are being developed to address complete vehicle systems, to detect faults in sensors and actuators, and to apply appropriate corrective action without adding new hardware to the vehicle. However, the high complexity of most vehicle systems makes

the standard FDI model-based technique difficult to apply without unacceptable computational effort.

The present invention is a novel system and method based on a hierarchical structure of the FDI scheme that reduces the computational effort of prior art systems. The FDI scheme uses the available sensors and actuators in a system such as a vehicle system and divides them into subsystems of smaller dimensions containing one or more modules that are related or interconnected. The same module may appear in a different subsystem, but the set of all subsystems does not have to contain all of the modules. For this structure, an FDI scheme comprising several detector units is created. Each detector unit receives information from the sensors and outputs a residual that is sent to a residual evaluation unit which processes the data and performs the residual evaluation for the selected subsystem. Finally, each subsystem outputs a decision that is sent to a supervisor unit performing the final diagnosis.

Brief Description of the Drawings

Fig. 1 is a block diagram of a vehicle model for an example embodiment of the present invention;

Fig. 2 is a block diagram of the general structure of a prior art model-based FDI method;

Fig. 3 is a block diagram of a residual generator in accordance with an example embodiment of the present invention;

Fig. 4 is a block diagram of a hierarchical diagnostic system in accordance with an example embodiment of the present invention;

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Fig. 5 is a block diagram for the structure of a fault detector unit in accordance with an example embodiment of the present invention;

Fig. 6 is a block diagram of a general module in accordance with an example embodiment of the present invention;

Fig. 7 is a block diagram of a fault detection and isolation unit in accordance with an example embodiment of the present invention;

Fig. 8 is a block diagram of the FDI scheme of the present invention;

Fig. 9 is a block diagram of the primary systems of a vehicle for an example embodiment of the present invention;

Fig. 10 is a block diagram of the primary components for a handling system for an example embodiment of the present invention;

Fig. 11 is a block diagram of the primary components for a propulsion system for an example embodiment of the present invention;

Fig. 12 is a block diagram of the primary components for a hybrid propulsion system for an example embodiment of the present invention;

Fig. 13 is a block diagram of the primary components for a hydraulic machinery example embodiment of the present invention;

Fig. 14 is a graph of steering wheel angle input;

Figs. 15-17 are graphs of estimated and actual state variables; and

Figs. 18-23 are graphs of experimental results for a J-turn.

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Detailed Description of the Invention

The present invention may be implemented in accordance with software components that provide the features and functionality described herein. The system and method of the present invention may be applied to any machine equipped with

5   sensors and actuators that requires reliability, safety, and availability.

Referring to Fig. 1 in an example embodiment of the present invention in which the system and method are applied to a vehicle control system, a vehicle may be represented, in general, as a block diagram as shown in Fig. 1 constituting of two main subsystems: the core subsystem 124 and the external subsystem. The core subsystem

10   124 comprises the vehicle 114, tire 120, powertrain 118, steering 112, suspension 116, and brake 108 modules. Each module may comprise one or more models adapted to accept input from one or more sensors and to process input to produce one or more outputs representing aspects of the model. The vehicle module 114 comprises a 16DOF vehicle model. The vehicle model further comprises a vehicle body, (i.e., the

15   sprung mass), and four wheels, (i.e., the unsprung masses). The model contains three translational degrees of freedom–longitudinal, lateral, vertical, and three rotational degrees of freedom–roll, pitch, and yaw for the sprung mass. Each of the unsprung masses has vertical, spin, and steering angle degrees of freedom. The tire module 120 has as inputs the longitudinal slip, the lateral slip, the vertical load, and the camber

20   angle which gives as output the longitudinal and lateral force as well as aligning moment. The powertrain module 118 comprises the engine, the transmission, and the differential models. The engine uses a lookup table with throttle position and engine speed as inputs and gives as output the engine torque. The transmission model inputs

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the engine torque and transforms the torque based on the selected gear. The differential model proportions the torque from the transmission to the drive wheels. The steering module 112 describes the elastic and geometric properties of the steering system. The suspension module 116 comprises the model of the suspension that may

5   be of four different types: linear spring and damper, nonlinear spring and damper, semiactive suspension, and active suspension. The brake module 108 generates the wheel torques as a function of the driver brake pedal force and brake controller commands.

The external subsystem comprises the environmental module 122, driver module

10   110, sensor module 100, brake controller module 102, suspension controller module 104, and communication module 106. The environmental module 122 determines the interfaces between the vehicle and the environment. The driver module 110 determines the interface between the driver and the vehicle. This module provides information such as brake pedal force, steering angle, throttle position, and desired gear to the core

15   module. The sensor module 100 models the sensor dynamics. The outputs of this module are sent to the controller module. The brake controller 102 and suspension controller 104 contain algorithms used to control the brake, and the suspension systems. The communication module 106 models communication delays which occur in communication links between controllers.

20   A vehicle in accordance with an example embodiment of the present invention may be a conventional automobile. In addition, a vehicle may be a truck, an earth mover, a crane, a bulldozer, a tank or any other heavy duty equipment or machinery. A vehicle may also be an airplane, a ship, or a railroad car or other type of passenger or

cargo transport vehicle. Any device capable of transporting persons or objects from one location to another in any manner may be considered a vehicle.

In the model-based FDI system and method of the present invention, analytical redundancy is used rather than physical redundancy. This analytical redundancy is contained in the static and dynamic relationship between the input and the output variables of the system. The sensitivity of a diagnostic method to modeling error is one of the key issues in the application of model-based FDI methods. In most cases, prior art model-based FDI methods can be described by the block diagram shown in Fig. 2.

When an accurate model of the vehicle is available, the general process of the model-based FDI consists of the three stages depicted in Fig. 3. At the first stage, observations 160 acquired through sensor measurements are compared to analytical values of the same variables in a primary residual generator 162. The error between measured and calculated variable is called a primary residual. This residual reflects the system behavior, and has nominal zero mean value under normal conditions. At the second stage, the primary residuals that usually deviate from zero due to noise, modeling error and faults, are communicated to a secondary residual generator 164 and converted in secondary residuals by means of filtering, statistical testing ,or spectral analysis to obtain signals that can be used to analyze and isolate faults. Finally, the secondary residuals are communicated to a decision maker 166 and analyzed to isolate the fault and a diagnosis 168 or decision is taken.

In accordance with the present invention, the vehicle system is decomposed into subsystems of smaller dimension containing one or more modules strictly related or interconnected. Referring to Fig. 4, for this structure, the FDI scheme comprises a

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plurality of fault detector units 186, 188, 192, 194, 198, 200. Each fault detector unit

186, 188, 192, 194, 198, 200 outputs a residual that is sent to a residual evaluation unit

184, 190, 196 that performs the residual evaluation for the selected subsystem

comprising the fault detector units. Finally, each subsystem that reports to a residual

5   evaluation unit 184, 190, 196 outputs a decision that is sent to a supervisor unit or fault

detector 182 performing the final diagnosis 180. As shown in Fig. 4, some different

subsystems for the vehicle are shown and each is constituted by a residual evaluation

unit 184, 190, 196 and a plurality of fault detector units 186, 188, 192, 194, 198, 200.

The scheme for a fault detector unit 222 is depicted in Fig. 5. Each fault detector

10   unit 222 may comprise a plurality of models 210, 212, 214, 216 and a primary residual

generator 218 that sends output to a residual evaluation unit 220.

In general, a module may be represented as in Fig. 6 where:

u_{0i}, $i = 1..m$ are the input vectors
Δu_i, $i = 1..m$ are the input fault vectors
θ_{0i}, $i = 1..m$ are the nominal parameter vectors
$\Delta \theta_i$, $l = 1..m$ are the parameter fault vectors
x_i, $i = 1..m$ are the state vectors
Δy is the output fault vector
y is the output measured vector.

20

The module can be described by the following equations

$$\begin{cases} \dot{x}_1 = f_1(x_1, u_1, \theta_1) \\ y = h_1(x_1, u_1, \theta_1) + \Delta y \end{cases}, \quad x_1 \in \Gamma_1$$
$$\vdots \qquad\qquad\qquad \vdots \qquad\qquad (1)$$
$$\begin{cases} \dot{x}_m = f_m(x_m, u_m, \theta_m) \\ y = h_m(x_m, u_m, \theta_m) + \Delta y \end{cases}, \quad x_m \in \Gamma_m$$

25   with $u_{0i} = u_{0i} + \Delta u_i$, $\theta_i = \theta_{0i} + \Delta \theta_i$, $i = 1..m$, and where Γ_i

is a subset in which the ith model equations are valid. A fault detector unit is associated with each module. Each fault detector unit contains a multimodel representation of the type

$$
\begin{cases}
\dot{\hat{x}}_1 = g_1(\hat{x}_1, u_1, \hat{\theta}_1, y) \\
\hat{y}_1 = h_1(\hat{x}_1, u_1, \hat{\theta}_1)
\end{cases}, \quad \hat{x}_1 \in \Gamma_1
$$
$$
\vdots \qquad\qquad\qquad \vdots \qquad\qquad (2)
$$
$$
\begin{cases}
\dot{\hat{x}}_m = g_m(x_m, u_m, \hat{\theta}_m, y) \\
\hat{y}_m = h_m(\hat{x}_m, u_m, \hat{\theta}_m)
\end{cases}, \quad \hat{x}_m \in \Gamma_m
$$

5   characterized by the fact that, without any fault, the following conditions hold

$$
\hat{x}_i \rightarrow x_i \quad \text{for } t \rightarrow \infty, \quad i = 1..n \qquad (3)
$$

Referring to Fig. 7, each fault detector unit 222, 252, 254 comprising a plurality of models 210, 212, 214 and primary residual generator 218 that generates the primary residuals 230, 240, 246 that are sent to the decision unit 236 as shown in Fig. 7. This

10   decision unit 236 may be a component of a residual evaluation unit 256 comprising secondary residual generators 232, 242, 248 and residual evaluators 234, 244, 250. The residual evaluations for the subsystem are performed at the residual evaluation units 234, 244, 250 and the result from the decision unit 236 is sent as input to the supervisor unit 238.

15   The method of the FDI scheme of the present invention comprises the following steps:

1. Partition of the vehicle model into subsystems containing one or more interconnected modules. The same module may appear in more then one subsystem, but the set of all subsystems, in general, does not have to contain all

20   the modules.

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2. Associate a fault detector unit to each module or smaller partition of modules and define a multimodel representation and selection of a residual generation method for every subsystem. The method for residual generation may be of different type, but commonly used approaches are the parity space method, the observer

5 method, and the parameter identification method.

3. Define an appropriate residual evaluation method for each subsystem.

During operation of the vehicle, data received at the fault detector units is processed and passed to the appropriate residual evaluation unit. A supervisor unit receives data from the residual evaluation units and diagnoses problems with the

10 vehicle.

To illustrate the method for a specific case, consider the subproblem of fault detection for three important sensors:

- the lateral acceleration sensor;

- the steering wheel angle sensor;

15 - the yaw rate sensor;

and for two parameters:

- the front cornering stiffness; and

- the rear cornering stiffness.

The structure of this example FDI scheme is shown in Fig. 8. One fault detector unit

20 260 is connected to a first primary residual generator 262 that connects to two residual evaluation units 264, 212. Three additional fault detector units 274, 276, 278 are connected to a second primary residual generator 280 that connects to three residual

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evaluation units 264, 272, 282, 284. Each residual evaluation unit 264, 272, 282, 284 connects to a decision unit 268 that provides output to a supervisor unit 279.

The FDI scheme of Fig. 8 shows a fault detector unit where only one multimodel representation for a simplified front wheel steered, small angle, bicycle model structure is considered. The dependence of the vehicle lateral velocity and yaw rate and the longitudinal velocity on the steering input is modeled. A simplified tire force model is adopted, whereby the lateral forces of the front and rear tires are linearly related to the front and rear slip angles, through Cf and Cr the front and rear cornering stiffness. The model is valid for nonsevere maneuvers, (i.e., for $a_{lat} \leq 0.2g$, where g is the acceleration due to gravity). The nonlinear model can be described by the equations

$$\begin{cases} \dot{v}_x = \frac{F_x}{M} + v_y \dot{\psi} \\ \dot{v}_y = -\frac{2}{M}(C_f + C_r)\frac{v_y}{v_x} - \frac{2}{M}(aC_f - bC_r)\frac{\psi}{v_x} - v_x \dot{\psi} + \frac{2C_f}{MG}\delta \\ \ddot{\psi} = -\frac{2}{I}(aC_f - bC_r)\frac{v_y}{v_x} - \frac{2}{I}(a^2 C_f + b^2 C_r)\frac{\psi}{v_x} + \frac{2aC_f}{IG}\delta \end{cases}$$

(4)

a	is the distance from front wheel to C.G. of the vehicle
b	is the distance from rear wheel to C.G. of the vehicle
C_f	is the front cornering stiffness
C_r	is the rear cornering stiffness
M	is the vehicle mass
I	is the vehicle moment of inertia
G	is the gear ratio
F_x	is the longitudinal force
v_x	is the vehicle longitudinal velocity
v_y	is the vehicle lateral velocity
δ	is the steering angle
Ψ	is the yaw rate

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For this model, it is possible to design the following sliding mode nonlinear

observer based only on the yaw rate measurement

$$\dot{\hat{x}} = \left(\frac{\partial H(\hat{x})}{\partial \hat{x}}\right)^{-1} M(\hat{x}) \operatorname{sign}(V(t) - H(\hat{x})) + B\delta \qquad (5)$$

where
$$H(x) = [h_1(x) \; h_2(x) \; h_3(x)]$$
$$h_1(x) = \dot{\psi} = r$$
$$h_2(x) = \dot{r}$$
$$h_3(x) = \ddot{r}$$
$$V(t) = [v_1(t) \; v_2(t) \; v_3(t)]$$
$$v_1(t) = r(t)$$
$$v_{i+1} = \left(m_i(\hat{x})) \operatorname{sign}(x(v_i(t) - h_i(\hat{x}(t))))\right)_{eq}, \quad i = 1,2$$
$$M(\hat{x}) = diag\left(m_1(\hat{x}) \; m_2(\hat{x}) \; m_3(\hat{x})\right)$$

The following table shows the error signatures.

Table 1. Error Signature

no.	fault variable	cause	resid. pattern
1	wheel steering angle δ	actuator failure	[1 0 1 0 1 1 1]
2	lateral accel a_{lat}	sensor failure	[1 0 1 0 1 0]
3	yaw rate r	sensor failure	[1 1 1 1 1 1]
4	Cf front cornering stiffness	blow out/ incorrect inflat.	[0 1 0 1 1 1]
5	Cr rear cornering stiffness	blow out/ incorrect inflat.	[1 1 1 1 0 1]

To simplify the problem, consider only the case of single faults. The residual vector is

$$R = [a_{lat} - \hat{a}_{y1} \; \delta - \hat{\delta} \; a_{lat} - \hat{a}_{y2} \; C_f - \hat{C}_f \; a_{lat} - \hat{a}_{y3} \; C_r - \hat{C}_r] \qquad (6)$$

With the choice made above, the error signature described in the Table 1 may be

derived.

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Some simulation and experimental results obtained from the previous FDI

scheme using sliding mode observers illustrate the system and method of the present

invention. The tests are carried out for a vehicle with the parameter data set as in table

2.

5   Table 2. Parameter Values Utilized in the Steering Model.

parameter	value
a	1.0 [m]
b	1.69 [m]
Cf	60530 [N/rad]
Cr	64656 [N/rad]
M	1651 [Kg]
I	2755 [Kg/m 2]
G	1
Fx	100 [N]

Although the present invention as has been described in accordance with a

vehicle handling system, the present invention may be used in conjunction with types of

other vehicle or machinery systems. Referring to Fig. 9, vehicles of many different

10   types may comprise a handling system 300, a propulsion system 302, and an auxiliary

system 304, each of which may comprise a plurality of modules associated with one or

more fault detector units that are connected to residual evaluation units and supervisor

units. Data may be exchanged between modules in each system to provide for optimal

vehicle performance.

Referring to Fig. 10, a handling system in a vehicle may comprise a brake controller module 102, a brake module 108, a steering module 112, a driver module 110, a tire module 120, a vehicle module 114, a suspension module 116, and a suspension controller module 104. As shown in Fig. 11, modules in the handling

5 system may communicate with modules in the auxiliary and propulsion systems.

Referring to Fig. 11, a propulsion system in a vehicle may comprise an engine controller module 310, a fuel module 312, an air intake module 314, a combustion module 316, a crank-shaft module 318, an exhaust module 320, and a transmission module 322. The modules in the propulsion system may communicate with modules in

10 the handling and auxiliary systems.

Referring to Fig. 12, a hybrid propulsion system may comprise a conventional propulsion system 330 as well as a supervisory controller module 332, a coupling module 334, an electric machine module 336, a controller module 338, and batteries/supercapacitors 340. The modules in the hybrid propulsion system may

15 communicate with modules in the handling and auxiliary systems.

Referring to Fig. 13, in a hydraulic machinery example embodiment of the present invention, a tank module 350, a pump module 352, a coupling module 354 in communication with a propulsion system 356, a controller module 358, a servo-valve module 360, and a cylinder module 362. The hydraulic machinery modules may

20 communicate with modules in the handling and auxiliary systems.

Referring to Fig. 14, the steering input for a vehicle lane change maneuver at a longitudinal velocity of 25-mph (11 m/s) and without any fault is shown.

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The relative state variable estimations (dashed line) are represented in Figs. 15-17. It is possible to notice that, after a fast transient, the estimates track the true variable with a very small error.

In Figs. 18-23, the experimental results for a Jturn at constant forward velocity

5 and step change in the steering angle are presented. A steering input fault of 1.25 times the commanded input has been applied during the test. Figs. 18 and 19 show the residuals for lateral acceleration and steering angle respectively obtained from Unit A1. In dashed line are indicated the estimate values from the observer, a flag 0 (threshold evaluation) may be associated to the lateral acceleration residual while a flag 1 is

10 associated to steering angle residual.

The residuals for lateral acceleration and front tire cornering stiffness obtained from Unit A2 are depicted in Figs. 20 and 21 while in Figs. 22 and 23 the lateral acceleration and the rear cornering stiffness are compared with the measured values. At the end, the following residual signature is observed

15     $R = [0\ 1\ 0\ 1\ 1\ 1]$ (7)

which indicates a steering inputs or C_f fault.

The present invention supports implementation of a vehicle health monitor to increase the reliability of a passenger or other type of vehicle with experimental validation of the observer design and FDI scheme. While particular embodiments of the

20 invention have been illustrated and described in accordance with vehicles, various modifications and combinations can be made without departing from the spirit and scope of the invention, and all such modifications, combinations, and equivalents are intended to be covered and claimed.